VSP and Crosshole Tomographic Surveys

1.0 PURPOSE.

1.1 To assure the accuracy, validity, and applicability of the methods used to image rock properties using Vertical Seismic Profiling (VSP) and cross-hole tomographic methods in the exploratory studies facility and accessible surface and subsurface boreholes; this procedure is a guide for Lawrence Berkeley National Laboratory (LBNL) personnel and contractors performing the described activity.

1.2 This procedure describes the components of the data acquisition, the principles of the methods used, and their limits. It also describes the detailed methods to be used for calibration, operation, and performance verification of any equipment, if needed. In addition, it defines the requirements for data acceptance, documentation, and control; and it provides a means of data traceability.

2.0 SCOPE.

2.1 This procedure applies to all YMP-LBNL personnel and their contractors who may perform work referred to in Para. 1.1, or use data obtained from this procedure.

2.2 For all technical activities, data collected from using this procedure and any equipment calibrations or recalibrations that may be required shall be in accordance with this technical procedure. Variations are allowed only if and when this procedure is formally revised, or otherwise modified, as described in Para. 8.

3.0 PROCEDURE.

This procedure establishes methods for obtaining seismic data that will be used to image the structure and rock characteristics between drifts, boreholes, and the surface. The results may be used to identify paths likely to cause radionuclide transport and to define the spatial extent of faults and fractures that may support fluid transport and affect the hydrological and geomechanical properties of the repository.

3.1 Objective: The objective of this work is to gather data in order to relate the P- and S-wave velocity, amplitude, and polarizations to rock properties and structure. The results will be used to define locations of fractured rock and details of the fracturing such as fracture orientation and fracture density as well as define major lithologic and structural boundaries. The ultimate objective of this work is to provide a subsurface image of the seismic properties of the repository-volume at survey scales ranging from a few meters to repository wide scales.

3.2 Methods Used: The general approach will be to use seismic sources on the surface and in boreholes to create P- and S-wave energy. This energy will be recorded in vertical and horizontal boreholes from the surface and in the exploratory studies facility. Also planned is crosshole work in the saturated zone (the C-holes are the locations of the initial work) to determine details of the rock structure for the interpretation of the tracer tests and crosshole hydrologic tests. Crosshole work will also be carried out in the unsaturated zone in the exploratory studies facility to monitor thermal, and thermal mechanical effects from the in situ heater tests, as well define structure and lithology.

3.2.1. VSP METHODS: In the strict definition of the term, VSP is recording seismic energy in a borehole with the energy source on the surface of the earth and a sensor (either a single or multi-component geophone) in a borehole at various positions within the borehole. Using this approach a vertical profile of seismic energy is obtained in the borehole or well, see Figure 1 of Attachment 1.

Prior to the initiation of the field work the accuracy of the depth measuring system will be checked and each day of the field work the vibrators must be checked. The depth at which the geophone is located in the hole is obtained by a digital depth counter that is checked by comparing the reading obtained by passing 100 meters of cable through the measurement device, to 100 meters actually measured using a commercial grade steel tape. If this measurement is off by over 0.25 meters then the proper adjustments to the depth counting system will be made before proceeding with the work. This depth checking procedure is repeated after each field session. The vibrators must be checked to insure proper phase matching with the recording system, and for proper power output. The vibrator and vibrator electronics will be checked according to the manufacturer's operating procedure. In general, the procedure is to run similarity tests of the input versus output of the source electronics and the mechanical output. In this way one can monitor the output to determine if it is as expected.

For geophones in the exploratory studies facility, a "tap" test will also be carried out which checks the polarity of the geophones and the signal level as well. After connecting the geophone to the cable each phone will be tapped on the top to check for wire continuity and proper channel recording. For geophones used in borehole VSP work where a clamped package is used a tap test will be performed at least at the start and end of each field session to check the response of the downhole VSP tool. The procedure is to set the VSP tool in a vertical orientation (within 10 degrees) and tap on the top and two horizontal directions of the tool. If the polarity is incorrect, or if there is no response then the defective geophone will be replaced.

The VSP procedure is to place a geophone(s), i.e., a device that measures the motion of the ground, in the borehole at either irregular or regular intervals by using a geophone(s) that can be clamped against the wall of the borehole. After the geophone has been placed at the desired point in the borehole the seismic source is activated for a short time period, usually no more than 20 seconds, and the data from the geophone, ground motion, is recorded. The data are recorded on a in-field recording device and saved on magnetic tape or disk. Each day a sine wave will be recorded of known frequency content and amplitude on the recording equipment using a sweep generator. The geophone(s) is connected to the recording device by a small gauge multiconductor, insulated, and shielded cable. The signals from the geophones are transmitted to electronics that filter, digitize, and record the data for further processing and interpretation. The recording will be done in a format that is in accordance with the Society of Exploration Geophysicists (SEG) standards (Digital Tape Standards, Society of Exploration Geophysicists, 1980). When needed, there are many commercial service companies capable of providing the field services. These services will be provided in accordance with applicable YMP-LBNL procurement procedures.

An oscilloscope and function (or sweep) generator will be used to check the signal levels and source driving signals of the system. The scope will monitor the shape and amplitude of the source signal throughout the survey. A function generator will be used prior to each field session to record a known wave form on the recording device to check for accuracy of the recording system. Only a five percent accuracy is needed in these checks due to the fact that the large variation in geologic properties has a much greater effect on the signals than a few percent deviation in source or signal strength.

At Yucca Mountain, seismic-profiling will also be carried out in the exploratory studies facility. Therefore, in reality there will be horizontal lines of geophones in the subsurface as well as vertical lines of geophones in the boreholes. The Exploratory Studies Facilities (ESF) VSP work will involve placing clampable, moveable, geophones in the exploratory studies facilities. Therefore, in a strict sense, the VSP work described here is not exactly conventional VSP work. In all ESF work there will be a three-component geophone at each recording interval. The three components are necessary to obtain S-wave in addition to P-wave information.

When vertical boreholes are used at Yucca Mountain, geophones will be placed at regular intervals (5 to 10 meters) in the borehole and then the energy source will be activated, and the data recorded. The geophone(s) is then unclamped and moved up the borehole (the geophone starts at the bottom of the borehole for the best depth control) the specified interval, and the procedure is repeated until the zone of interest in the borehole is traversed. Geophone depths are measured to 0.25 meter precision using a steel cable. Distances along drifts are measured to 0.1 meter using a commercial grade steel tape. An operational check of the steel cable shall be as follows: a zero point is marked on the cable, the cable is then lowered to the deepest desired point in the borehole. The cable is then reeled up in the desired increments until zero point is reached again. This procedure checks the repeatability of the instruments measuring the depth in the borehole. The strike direction of the geophones are usually obtained within 10% from seismic data, and 5% when measured by Brunton compass.

In the ESF and drift work, strings of geophones will be placed in ramps and along the drift walls, rather than having a few geophones that must be repeatedly moved. This will reduce the amount of time necessary to record the data when performing tests in the ESF. This is important to note because during seismic recording all other activities that cause seismic noise within the bandwidth of interest must be minimized. In the drifts the geophones will be attached to the walls via a clamp on a small aluminum plate that has been epoxied to the wall on intact rock. Aluminum is necessary because of its similar density to rock. P-wave and S-wave vibrators will be used as energy sources at the surface of the earth. These sources will be positioned at regular intervals along lines trending parallel, intermediate, and perpendicular to the strike of the major fault and fracture directions. Fracture and fault directions will be obtained from the ESF drift wall geologic mapping and from known surface mapping. The offset distances from surface boreholes and ESF facilities will be every 200 to 250 meters (depending upon access), with up to 5 offsets along each line. At each offset we will activate the P-wave source, and the S-wave source. The S-wave source will be vibrated parallel, and then perpendicular to each line. Each vibration sequence will be done at each geophone level in the well and for each line of geophones in the ESF facilities.

Where possible in VSP studies in vertical boreholes, we are purposely extending the work to below the water table to determine the seismic signature and sensitivity to P- and S-waves of the saturated zone relative to the unsaturated zone. Preliminary examination of well logs in wells surrounding this area show generally an increasing velocity with depth, but intermixed with low velocity zones. There is also a very near surface high velocity zone.

3.2.2 CROSS-HOLE TOMOGRAPHIC SURVEYS: Beyond VSP lies the emerging crosshole technique. It offers the most promising approach for increasing resolution significantly. The quantities measured are the same as VSP, but geometry and processing of the data can vary significantly. Therefore, a discussion will be included to reflect this difference. Crosshole and tomographic techniques usually involve placing a source in one borehole and a string of receivers, or a moveable receiver in another borehole. The advantages gained by placing the source in a borehole are the additional spatial coverage obtained for image construction as well as the elimination of the attenuating surface layer from the source receiver path. Figures 2 and 3 of Attachment 1 illustrate two common borehole survey methods.

As stated previously, the quantities measured in tomographic studies are the same as for the VSP methods, a time series of information so that amplitude and time are measured, but the geometry of the data collection is different. As applied to the Yucca Mountain case the methods actually overlap. In the drifts when strings of receivers are set out the data collection will be in a geometry that will lend itself to tomographic reconstruction when multi-source points are used on the surface of the earth. In this case one borehole will be the surface of the earth and one will be the drifts. Tomographic reconstruction will also be possible for the VSP data when multi-offset configurations are used along straight lines. Imaged will be the P-, and S-wave (SH and SV) properties as well as their ratios of velocities and amplitudes for the VSP, as well as tomographic cross-well data.

When crosshole data are collected it is obvious that the source must also fit into the borehole. For this reason the sources used for crosshole seismology are smaller and less powerful than the large surface sources used in VSP work. Because of this, the frequency content is also higher, up to several kilohertz, thus allowing higher resolution. It is not uncommon to have 5 to 10 kilohertz frequency content in the seismic waves for crosshole work at distances of tens of meters. Even at distances of hundreds of meters the frequency content of the waves is several hundred hertz to over a kilohertz. Because of the tomographic imaging nature of this work, it is necessary to have as many raypaths as possible for transmission tomography, and a considerable amount more than VSP for diffraction tomography. However, the resolution is greatly enhanced with this method over conventional VSP work.

The actual field procedure involves placing a seismic source in one borehole and a receiver in another borehole. The boreholes need not be parallel, but they could also be perpendicular if a third borehole is used. The deviation log which is usually completed after the borehole has been drilled will be used to document the location of the sources and receivers. It is best to have four sided tomography, i.e., coverage on all four sides of the area of interest, but the method also is applied in two- and three-sided cases. Because of the high frequencies used, the receiver is usually not a geophone, except where the frequencies are below 100 hertz, but an accelerometer or a hydrophone. This is for improved electronic signal to noise ratio.

At the beginning of each day the accelerometers or hydrophones will be checked for operation by placing them at a specified point and activating a source. At the beginning and end of each field session each accelerometer's or hydrophone's performance is checked against an accelerometer or hydrophone which has not been used in the field. This reference signal will then be a calibration for all subsequent data. If there is a significant difference from one day to the next (greater than 2 percent) then previously gathered data will be disregarded and the accelerometer or hydrophone will be replaced with another until tolerance is met.

The collection of the data is essentially the same procedure as for VSP, except many more data points are gathered because of the redundancy in the source and receiver points. The data are also collected on a in-field system that filters, stacks, and digitizes the data before the data are recorded on disk or magnetic tape. The data rates will depend upon the scale of the tomographic surveys, but the maximum data rate will be 250,000 samples per second per channel for detailed high frequency tomographic imaging. The spatial sampling will range from 10 meters in the ESF to 0.25 meters in boreholes to monitor detailed processes around heaters and canisters in the ESF facilities. The process is to place the source at one spot and move the receiver the desired length of the hole. The source is then moved to the next location and the receiver is again moved the entire length of the hole. The process is repeated until the source has been moved to all desired points (Figure 2 and 4). This is repeated for each pair of source and receiver boreholes and/or lines of the work. In the case of the piezoelectric source electronics, a 100 MHz oscilloscope will monitor the output shape and amplitude of the signal. This value will be compared to the indicated signal on the source electronics itself. If more than 1 percent deviation is noticed, it will be noted and the voltage adjusted to tolerance.

An important aspect of this work is proper source and receiver mounting or clamping in the boreholes. Due to the high frequencies there can be severe coupling problems at several kilohertz. Therefore the sources and receivers are hydraulically clamped into dry holes with a pressure of at least 100 pounds per square inch. Insufficient clamping or mounting is readily apparent in the data quality, indicated by a sudden change in the signal strength. In water filled holes the coupling is more consistent. In this case clamping of the source and the receiver is usually not necessary, however, the stationary device (i.e., if the source is being moved the receiver is the stationary device, and vice versa) is clamped to prevent movement and ensure accurate station location. In deep, vertical, water-filled boreholes, strings of hydrophones will be used as receivers. In this case clamping is not possible, therefore it will be necessary to lock the cable that holds the hydrophone string to prevent inaccurate receiver location.

The data are acquired in sequence, one set of receivers at a time, until all of the source and receiver points are covered. There are various commercial recording systems available to meet the multichannel (8 minimum) and high frequency (up to 1 megahertz total throughput) criteria.

3.3 Materials/Equipment Required:(No special handling, storage and/or shipping is required unless otherwise noted.) The equipment needed will vary depending upon the application. When necessary, to minimize the cost almost all major items will be provided by qualified service companies. These services will be provided in accordance with applicable YMP-LBNL procurement procedures.

3.3.1 VSP WORK, SURFACE BOREHOLES:

o Multi-channel digital (16 bit) field recording system, as described above.

o 7 conductor, low-temperature wireline, long enough to reach the bottom of the hole, mounted on a winch truck. The wireline must also have a cable head that matches the geophone assembly and a 7 conductor slip ring that allows the signals to be connected to the recording device without repeated connecting and disconnecting of the recording system to the wireline assembly. The wireline equipment must be capable of an accuracy of 0.25 meters location in the hole.

o Clampable 3-component geophone(s). The geophone assembly consists of sensing elements, amplifiers (40 to 60 db) for each sensing element, a clamping mechanism, and in some cases an orientation device. Located at the surface are the power electronics and the control for the clamping mechanism for the geophone.

- o P- and S-wave vibrators (at least one each). The vibrators must be capable of producing at least 25,000 pounds of force.

- o Radio controlled trigger. The recording system and vibrator must be matched with radio controlled triggers of the sources with a phase accuracy of 5 degrees or less. The radio trigger must be able to transmit the trigger with a power output of 25 watts RMS or more.

- o Commercial grade steel tape.

NOTE: The same equipment will be required for the large scale crosswell work except the source will be a piezoelectric borehole source.

3.3.2 EXPLORATORY STUDIES FACILITY WORK: In the ESF work, the wireline equipment will not be used.

- o Multi-channel digital (16 bit) field recording system. A roll along switch will be necessary if a recording system less than 128 channels is used. This switch allows "rolling" along the geophones without physically rewiring the connections to the recording system. The surface recording equipment will be housed in a dedicated vehicle with its own power.

- o 3 component geophones. The geophones will be emplaced in either shallow boreholes along the ramps or attached to the walls. Thus the geophones need not be of the clampable type used in the VSP work. They will be individually placed along the ramp. In the drifts the geophones will be mounted on the side of the wall clamped to small (6-inch diameter) aluminum plates epoxied to the rock.

- o A dedicated 128 conductor cable, with 3 take outs every 10 meters, will run the length of the desired study area. The 3-component geophones will be attached to this cable when it is time to record the data. The cable will be connected to the recording system. The cable in the drift must have a mating cable connector compatible with the cable used in the shaft. This will eliminate the need for another cable to be run in the shaft to connect the drift geophones to the recording equipment on the surface of the earth.

3.3.3 CROSSHOLE TOMOGRAPHIC WORK:

- o A minimum of 8 channel high frequency, (one megahertz throughput over 16 channels) digital, (12 bit minimum) triggered, recording system will be necessary.

- o A clamped piezoelectric source capable of producing enough energy to transmit 5 kilohertz energy through approximately 100 meters of rock that has a quality factor of about 100 or greater (Q equals delta E over E, were E signifies energy per seismic cycle).

- o Electronics to power the piezoelectric source, i.e., a high voltage (up to 10,000 volts may be necessary, at 0.5 amp) source to pulse the piezoelectric borehole transducer. The source electronics must be capable of putting out a pulse with a rise time of less than 50 nanoseconds, and a variable width of 100 to 2000 microseconds. A plus 5 volts (TTL) trigger pulse must coincide within 10 nanoseconds of the onset of the pulse to the piezoelectric transducer.

- o High voltage cables and connectors, RG-58U or equivalent, to connect the piezoelectric transducer to the power source.

- o A clamped three component accelerometer receiver package with a frequency response to match the scale of the experiment. In most cases this will be from 1,000 to 10,000 hertz. The receiver package(s) must have enough low noise cable (coaxial) to connect to the recording equipment. The receiver package must be capable of having interchanging accelerometer elements for inserting different accelerometers for higher or lower frequency ranges.

3.3.4 TEST EQUIPMENT:

- o Oscilloscope - single channel, 100 Mhz; 5% accuracy over the range of 500 hz to 15 Khz

- o Sweep generator - capable of producing the sine wave with a frequency content between 10 hz and 15,000 hz; 3% accuracy over the range of 500 hz to 15 Khz

In addition to the equipment above there will be various supplies, spare parts, magnetic tape, field notes, and recording logs.

3.4 Assumptions Affecting the Procedure: In addition to the assumptions as described in the detailed procedure, we are assuming that the seismic signals recorded are mainly from the controlled sources used. There will be noise associated with the data but it is assumed that by proper planning and scheduling the significant noise associated with construction activities can be avoided.

3.5 <u>Data Information</u>: The data will be recorded on magnetic tape with backup copies stored at LBNL.

The data will be digitally recorded on a multi-channel, 16 bit system in SEG format. An example of an acceptable system is a Texas Instrument DFS-V, with the necessary anti-alias filter and gain capabilities. The sweep rates and recording times will be dictated by the actual field conditions, but we are anticipating a 2-mil sample rate with sweep frequencies from 10 to 100 Hz for the P-wave and 10 to 60 hz for the S-wave. The data will be recorded on 9-track tapes and taken from the field for processing.

The data will be in the form of petroleum industry standard SEGY and/or SEGB format or in standard ASCII format. These data are time series data recorded on a field recording system. The number of time series will depend upon the number of recording levels in the wells and exploratory studies facility. For example, it is anticipated that in each deep well (500 meters) used there will be at least a total of 50 levels, 12 offsets, and 9 traces per offset per level, for a total of 5400 traces.

3.5.1 QUANTITATIVE/QUALITATIVE CRITERIA: Data will be acquired when the signal to noise ratio exceeds a factor of two. The locations of the sources and receivers must be known to within 0.5 percent of the survey dimension for VSP work, and 0.1 percent for high frequency (greater than 5 kilohertz) tomographic imaging work.

3.6 <u>Limitations</u>: The primary limitation will be the spatial coverage, frequency content, and noise contamination of the seismic signals. Spatial coverage and frequency content are primarily access problems and problems with obtaining seismic sources with sufficient strength and bandwidth. This is primarily seen as a problem for the cross-hole tomographic imaging work. However, as time passes new and improved borehole sources and receivers are being developed for other applications. It is anticipated we will be able to take great advantage of these technology developments in the next five years. Noise problems are addressed by either using stronger seismic sources, filtering the data, or eliminating or reducing the noise source.

3.7 Other: The software used to digitize and store the data is identified as "X-ACQ", which has been documented in accordance with YMP-LBNL-QIP-SI.0, Software Quality Assurance.

3.8 Calibration Requirements Due to the low required accuracy for the oscilloscope and function generator, calibration is not required but may be done by any commercial vendor at the discretion of the PI.

3.9 Identification and Control of Samples Samples will not be collected or handled as part of this procedure.

4.0 **RECORDS MANAGEMENT**. Documents and data will be prepared and submitted per YMP-LBNL-QIP-17.0.

4.1 Anticipated documents and data generated from implementation of this procedure will include the following: the magnetic tapes from the recording equipment, observer logs, locations of the sources and receivers, and records of operational checks and calibrations. Lifetime records will be kept in a suitable format.

4.2 Notebooks, forms, or other organized documentation shall be prepared, as appropriate, by the PI or a contributing investigator to record data from this procedure and shall include the date of data collection, the unique identifier of equipment used to collect/record the data, the identification of the investigator, and any information considered by the originator to be pertinent. When in loose-leaf form, each page shall be numbered consecutively and chronologically. Any revisions shall be lined out, initialed, and dated. Notations by pencil shall be submitted in legible photocopy form.

5.0 RESPONSIBILITIES. The Principal Investigator (PI) is responsible for assuring full compliance with this procedure. The PI shall require that all personnel assigned to work to this procedure shall have the necessary qualifications and training to adequately perform the procedure; and they shall have a working knowledge of the YMP-LBNL QA Program. Responsibilities of others including the reviewer(s); contributing investigators; QA Manager and LBNL Project Manager are as described in YMP-LBNL-QIP-5.1. When procedure-specific responsibilities are to be delegated to contributing investigators or other personnel, the details of these responsibilities are as stated in this procedure. Special qualifications and/or training unique to the conduct of this procedure are as follows: In the acquisition phase of the project, trained personnel are needed to emplace the sensors and electronics in such a manner as to minimize the acoustic noise from the surroundings. If necessary, all ongoing investigations shall be identified, at the location of the scientific investigation, to preclude inadvertent interruption and to ensure compatibility of the investigations.

6.0 ACRONYMS AND DEFINITIONS — NONE.

7.0 REFERENCES

Digital Tape Standards, Society of Exploration Geophysicists, 1980.

YMP-LBNL-Quality Implementation Procedure: YMP-LBNL-QIP-5.1.

YMP-LBNL-Quality Implementation Proedure: YMP-LBNL-QIP-17.0.

YMP-LBNL-Quality Implementation Procedure: YMP-LBNL-QIP-SI.0.

8.0 ATTACHMENTS.

Attachment 1: Figures 1, 2, 3, and 4 as referenced in Section 4.2.

9.0 REVISION HISTORY

None

10.0 REVIEW AND APPROVALS.

Preparer Date	Principal Investigator Date
Technical Reviewer Date	YMP-LBNL QA Manager Date
QA Reviewer Date	YMP-LBNL Project Manager Date